

Spacecraft VLBI and Doppler tracking of Venus Express

G. Molera Calvés, D. Duev, G. Cimò, S. Pogrebenko, L. Gurvits,
T. Bocanegra-Bahamón

Joint Institute for VLBI in Europe (JIVE, the Netherlands)

e-mail: molera@jive.nl

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Overview

- Introduction to PRIDE and the VLBI technique
- Science with PRIDE and targets
- Processing pipeline
- Results
 - Determination of the state vectors of VEX spacecraft
 - Mars Express Phobos-flyby
 - VEX Drag campaign
 - Interplanetary scintillation study
- Conclusions

Generic PRIDE configuration

Planetary Radio Interferometry and Doppler Experiment

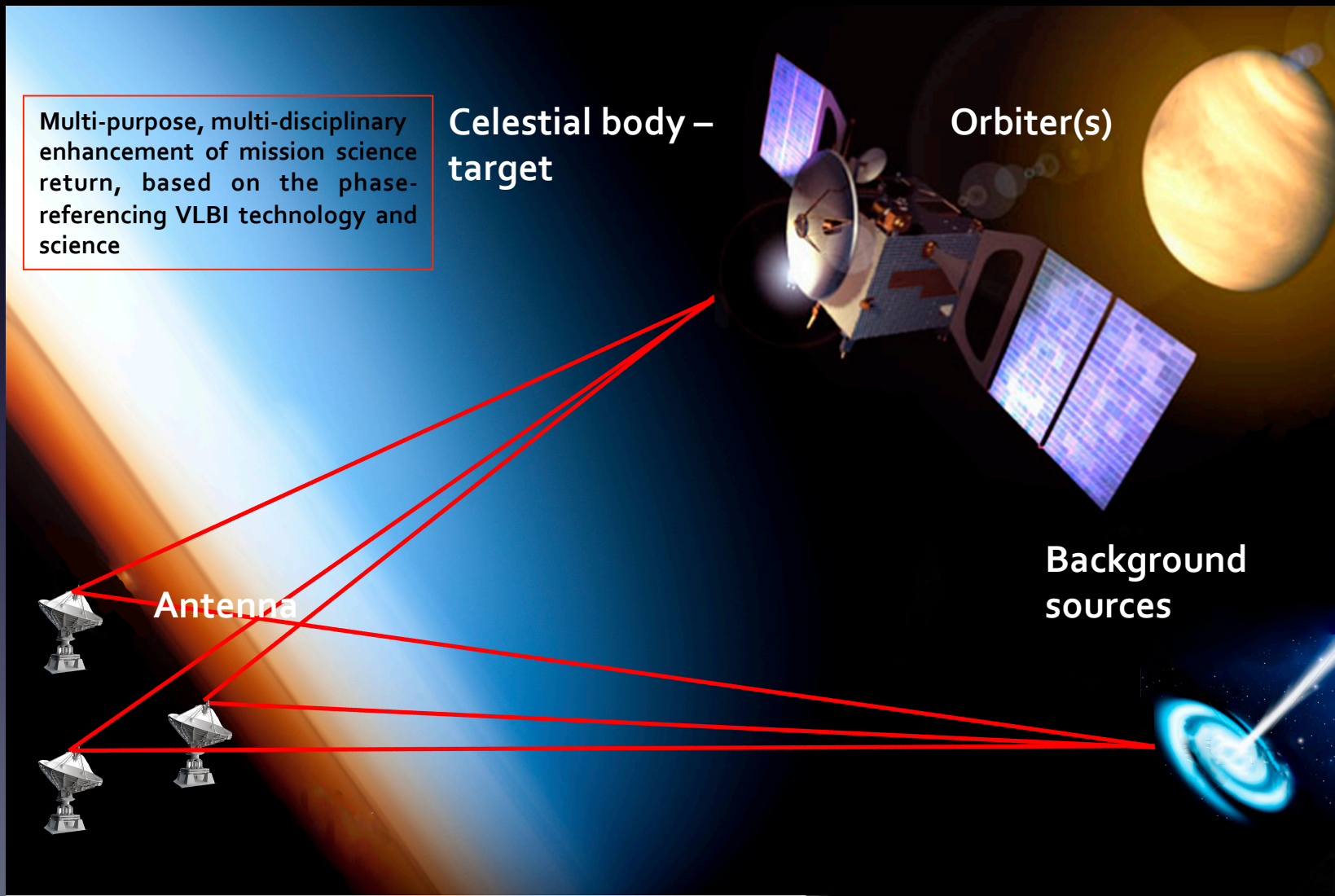
Multi-purpose, multi-disciplinary enhancement of mission science return, based on the phase-referencing VLBI technology and science

Celestial body – target

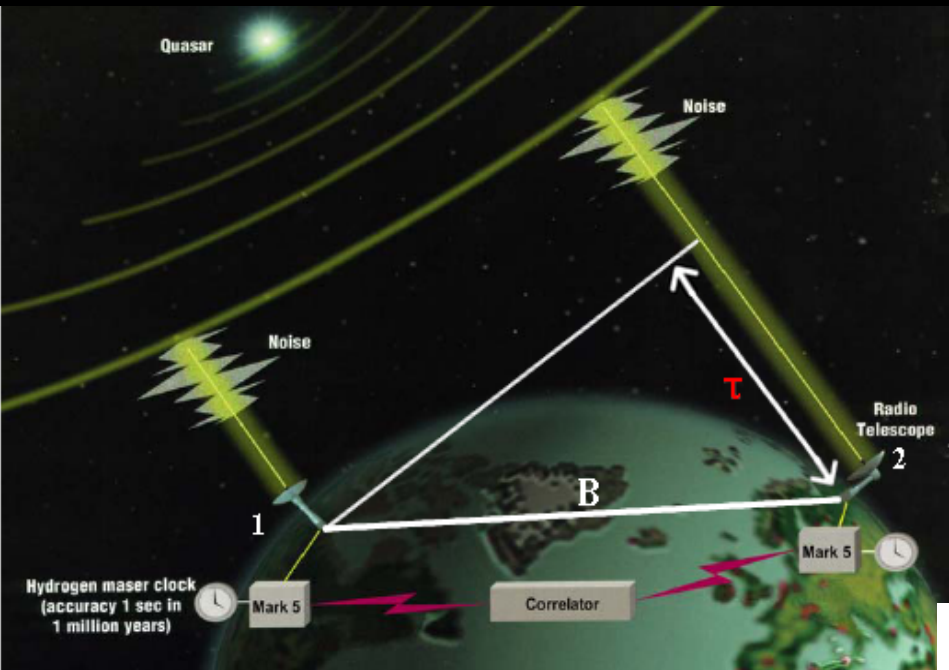
Orbiter(s)

Background sources

Antenna



Very Long Baseline Interferometry (VLBI)



Radio interferometry concept

Two radio telescopes observed at the same time the radio signal emitted by any celestial source. The different arrival time of a wave is the **delay time** ' τ ' and maximizes the correlation of the input signals.

More than 20 radio telescopes are members of the EVN consortium. EVN conducts regularly VLBI sessions several times per year.

The current correlator node is at **Joint Institute for VLBI in Europe (JIVE)**, the Netherlands.

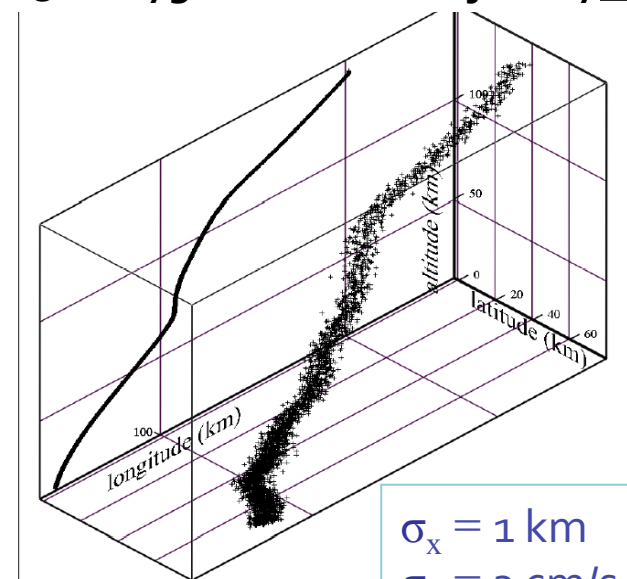


Huygens VLBL heritage

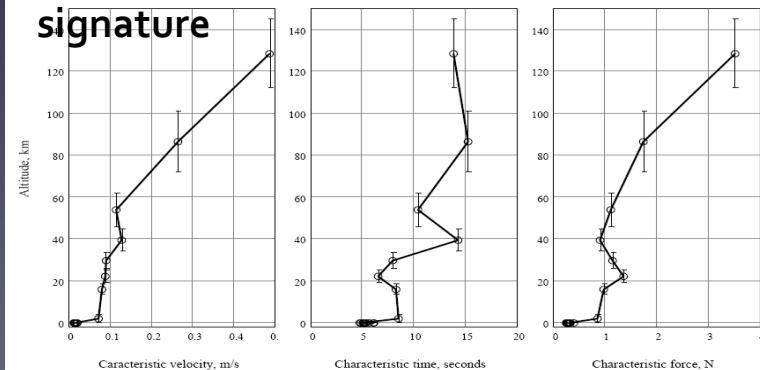


- Ad hoc use of the Huygens “uplink” carrier signal at 2040 MHz
- Utilised 17 Earth-based radio telescopes
- Non-optimal parameters of the experiment (not planned originally)
- Achieved 1 km accuracy of Probe’s descent trajectory determination
- Assisted in achieving one of main science goals of the mission – vertical wind profile

3D Huygens descent trajectory



Titan atmosphere turbulence signature



Science with PRIDE

VLBI estimates of the S/C state vector

- Study of the propagation of radio waves natural and artificial in our Solar System.
- Ultra-precise celestial mechanics of planetary systems;
 - measurements of tidal accelerations of the satellites.
- Geodynamics, internal structure & composition;
 - Powerful constraints on the interior structure, topography and gravity field of the moons.
- Shape and gravimetry;
 - multiple flybys can be used to define the low order gravity field parameters.
- Electric properties of icy satellite surfaces and their environments;
 - PRIDE will bring in multi-antenna detections enabling “stereoscopic” view of phenomena.
- Anomalous accelerations of deep space probes and other *fundamental physics effects*.

+ “Cruise” science plus mission diagnostics

+ Direct to Earth (DtE) radio link

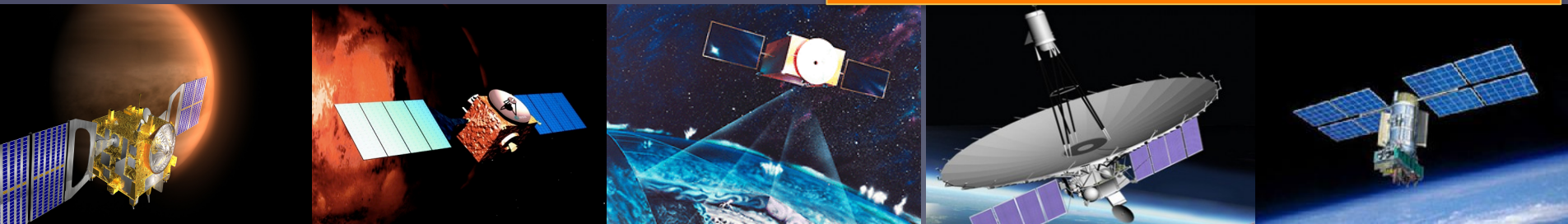
PRIDE targets

Current (possible) PRIDE targets

- ESA Venus Express (VEX)
- ESA Mars Express (MEX)
- JAXA Akatsuki & Ikaros
- NASA Stereo A/B
- NASA Mars Rover
- NASA Ulysses
- GLONASS satellites
- RadioAstron Space VLBI mission

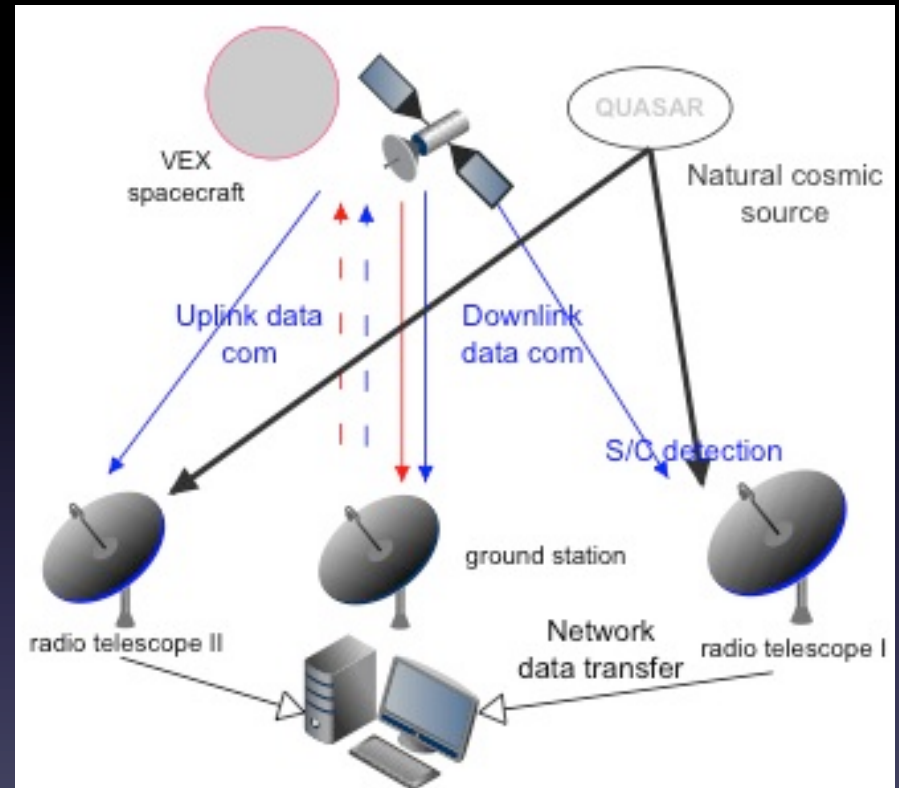
Prospective PRIDE missions

- Phobos/Soil
- ESA GAIA 2013
- ESA-JAXA Bepicolombo 2015
- ESA ExoMars 2016
- ESA Jupiter Icy Europa moons 2020.
- ESA MarcoPolo-R 2020
- RSA Venera-D 2024



VLBI Doppler tracking configuration

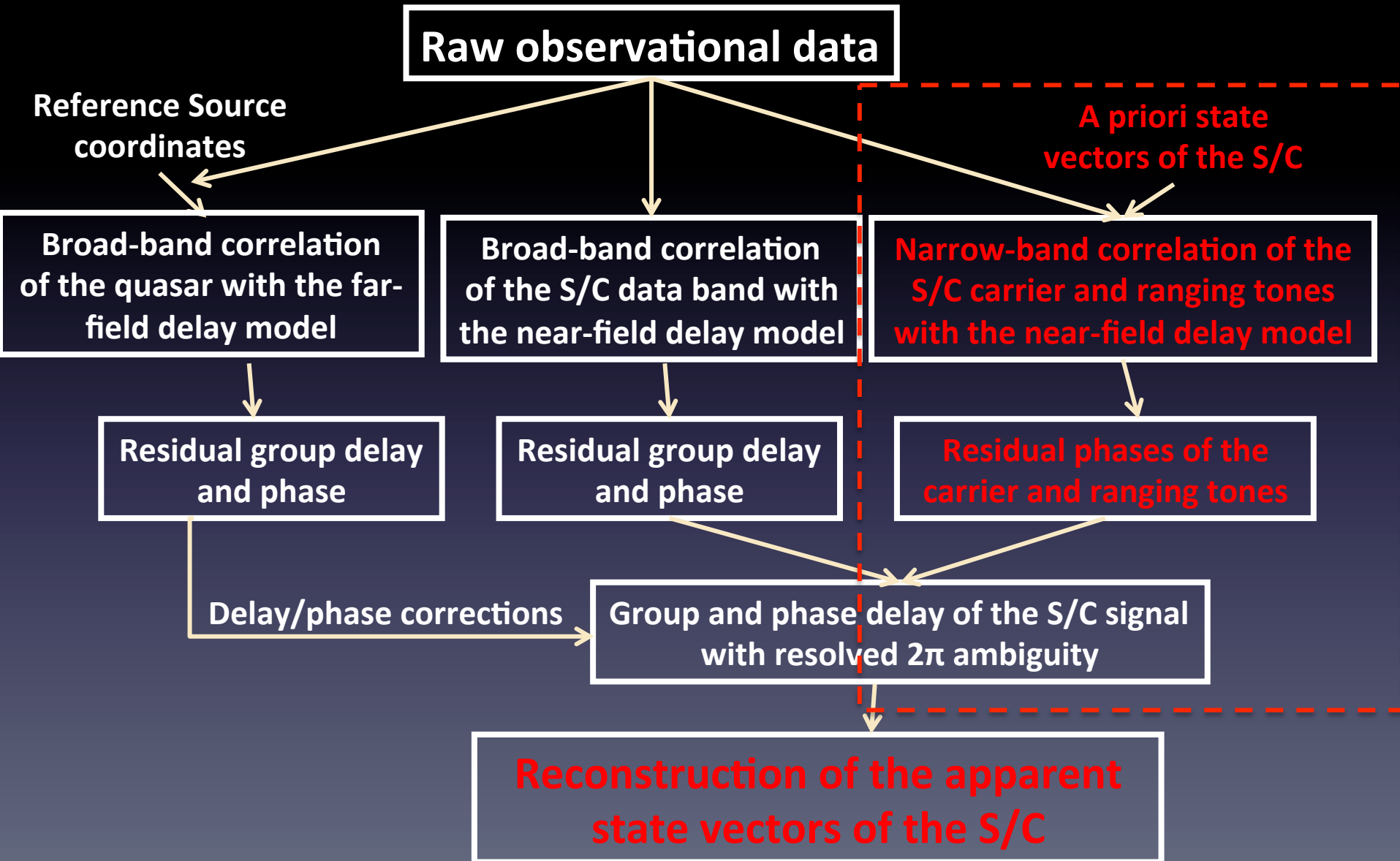
- During the observations the antennas alternate targeting the spacecraft and the background reference source.
- VLBI phase-referencing is a technique that allows calibrate the data from the spacecraft with the well known celestial reference.
- The celestial source may be up to 4 degrees apart from the spacecraft in angular terms (Ros et al., 2000).
- The nodding cycle depends on the telescopes sensitivity, spectral resolution and size of the array: typical values between 60 seconds to 5 minutes.



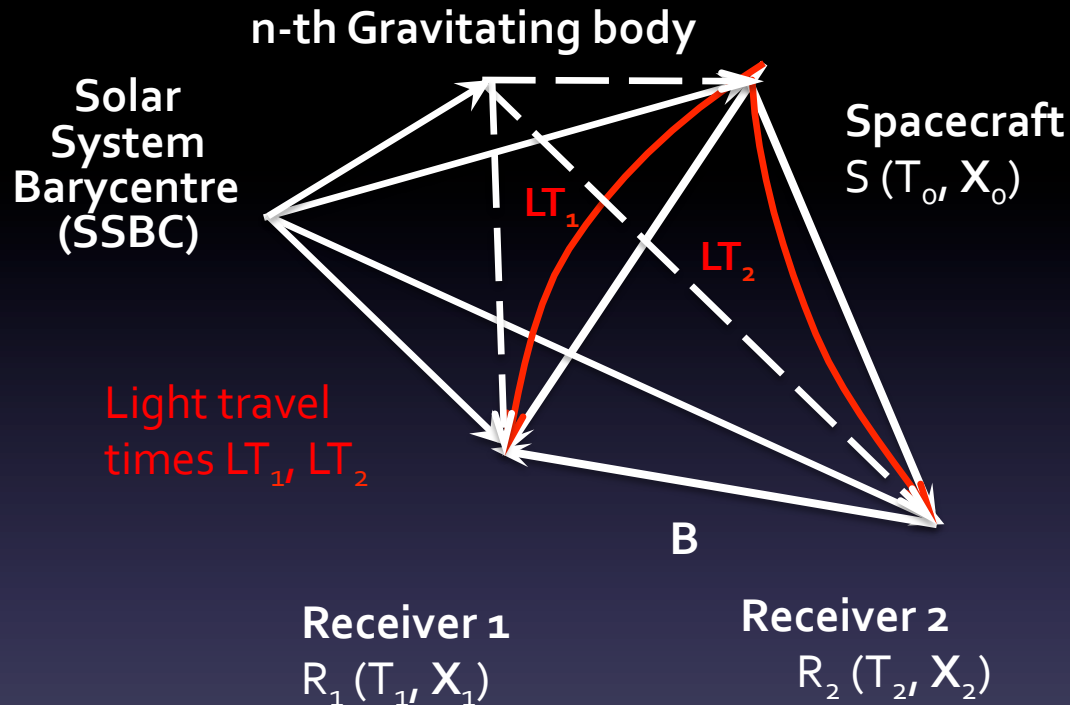
VLBI telescopes used to record large bandwidth of the data (128 or 256 MHz) separated into 8 or 16 MHz frequency channels.

→ S/C signal is compressed in only few Hz

Block-diagram of data processing and analysis



Near-field VLBI delay model



Receiver positions:

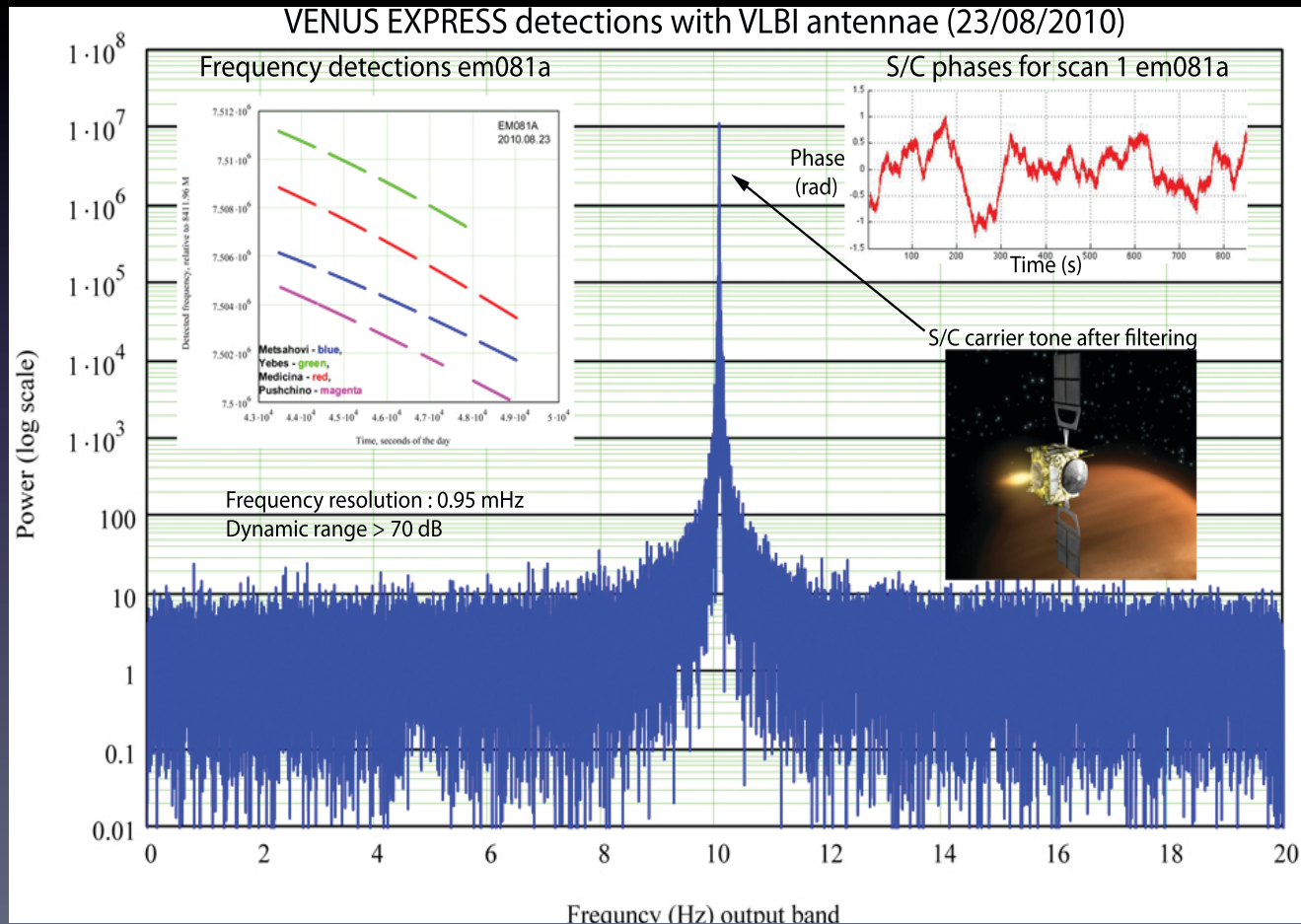
- ITRF \rightarrow GCRF
(IERS Conventions 2010)
- Plate tectonics, ocean loading, solid Earth tides, pole tide, atmospheric loading
- Thermal and gravitational deformations of telescopes
- Lorentz transformation
GCRF \rightarrow BCRF

Geometry of VLBI observations of spacecraft in the Barycentric Celestial Reference System

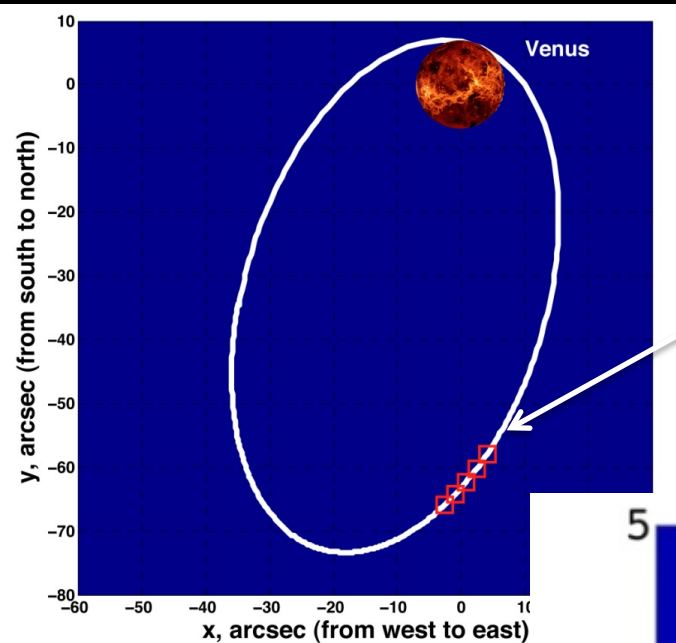
Delay in the **BCRS** $\tau := LT_1 - LT_2$, taking into account relativistic terms
Finally, τ is Lorentz-transformed into the Geocentric TT-frame

Detection of spacecraft in narrow band

Detection of the spacecraft signal viewed for 4 different radio telescopes in a narrow band of 20 Hz around the carrier with a frequency resolution better than 1 mHz.



Results: VEX observations



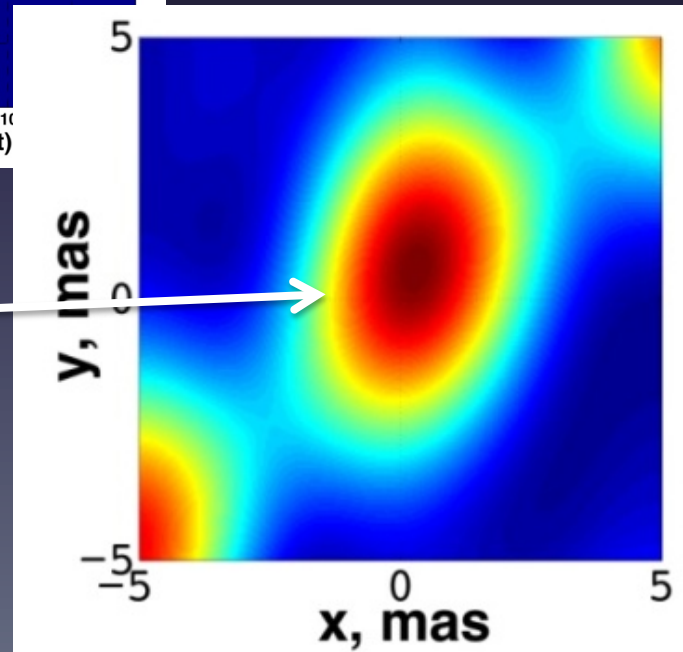
VEX orbit during the session

VLBI and Doppler tracking experiment (em081c) observed with 11 radio telescopes on 2011.03.28:

- 7 Europe
- 2 Russia
- 1 Africa
- 1 North-America

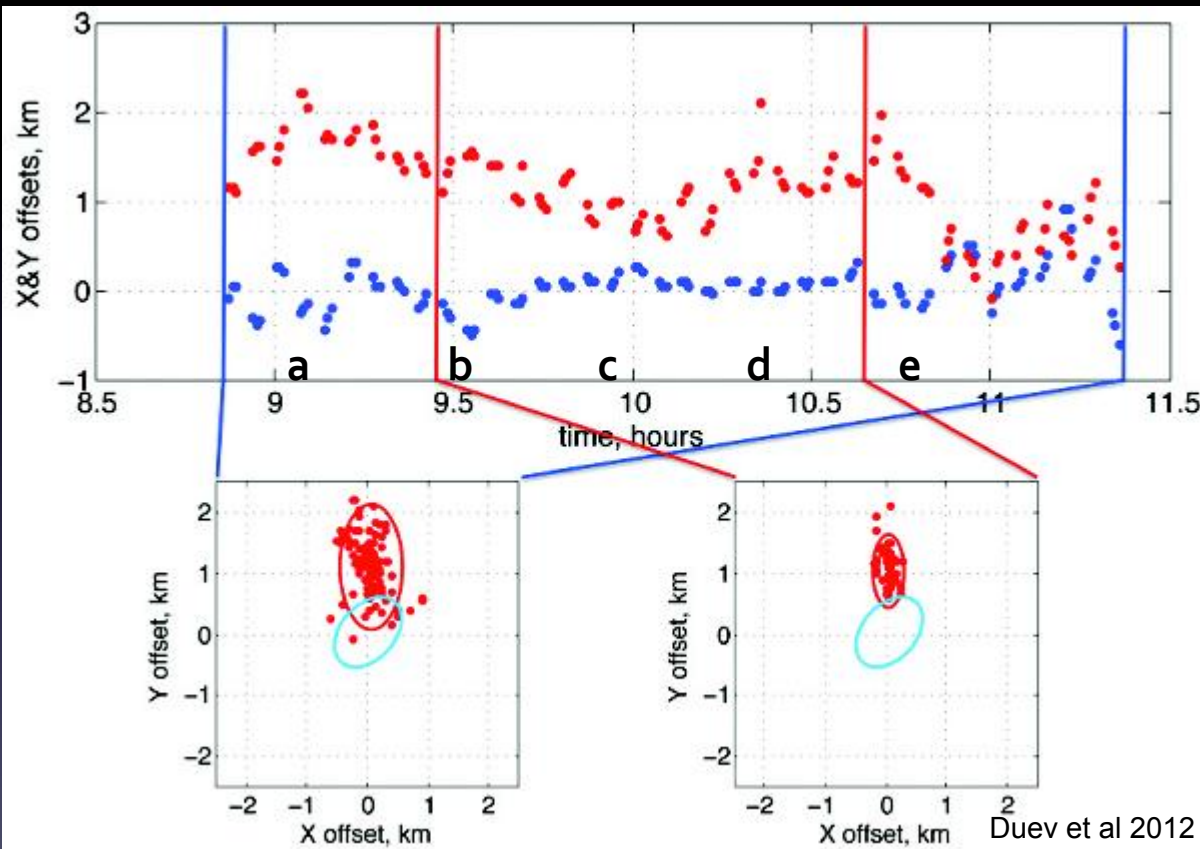
The radio telescopes alternated observing the natural reference source (+5 min) and VEX spacecraft (+5 min).

(Duev et al., 2012)



Instantaneous reconstructed image of VEX (point-like source)

Determining position of VEX



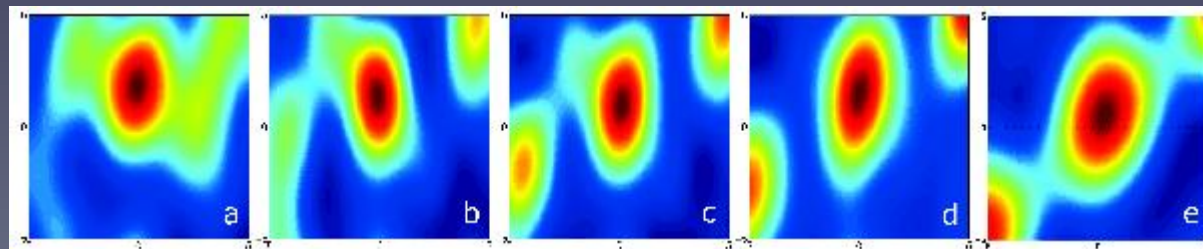
Measured offsets wrt
a priori trajectory
(ESOC)
X— red, Y— blue.

The integration time for each point is 30 s.

Blue ellipse: ESOC prediction
Red points: EVN data

The orbit accuracy estimate is at a 3 sigma level of 200 m
across the track and 500 m along the track.

The averaging time for
each image is 20 min.

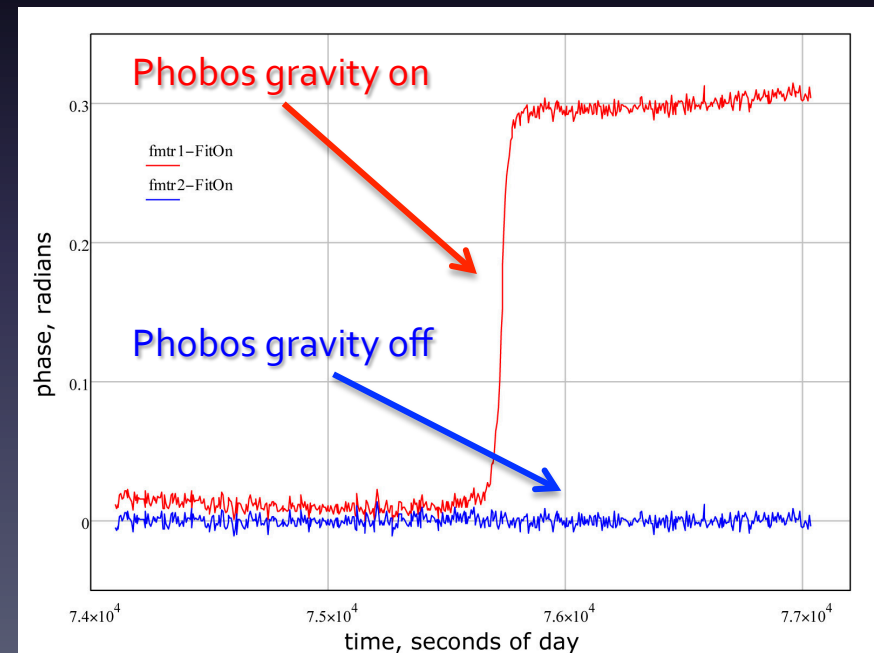
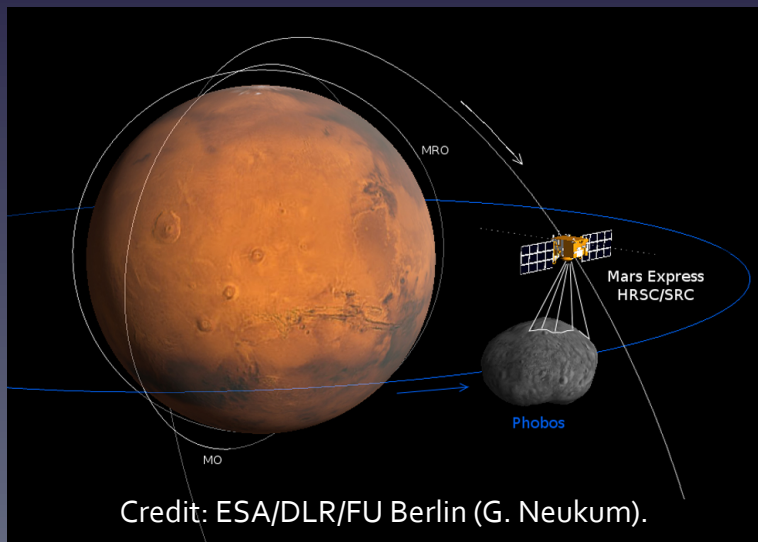


Other RS experiments

The **fly-by of Mars Express (MEX)** to the Martian moon Phobos.

3 EVN radio telescopes: Yebes (Spain), Wettzell (Germany) and Metsähovi (Finland) observed on 04 March 2012 the fly-by.

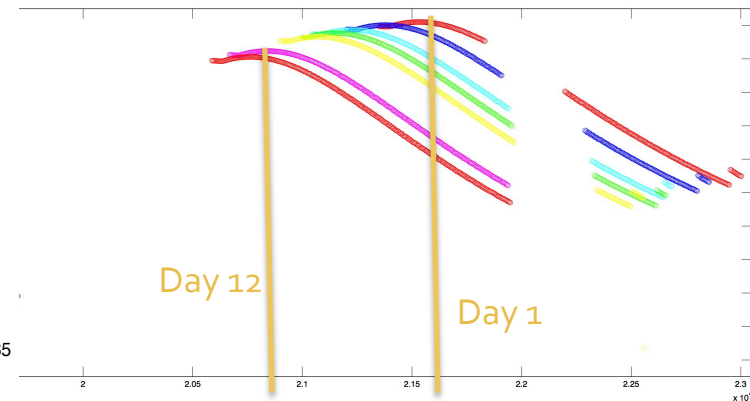
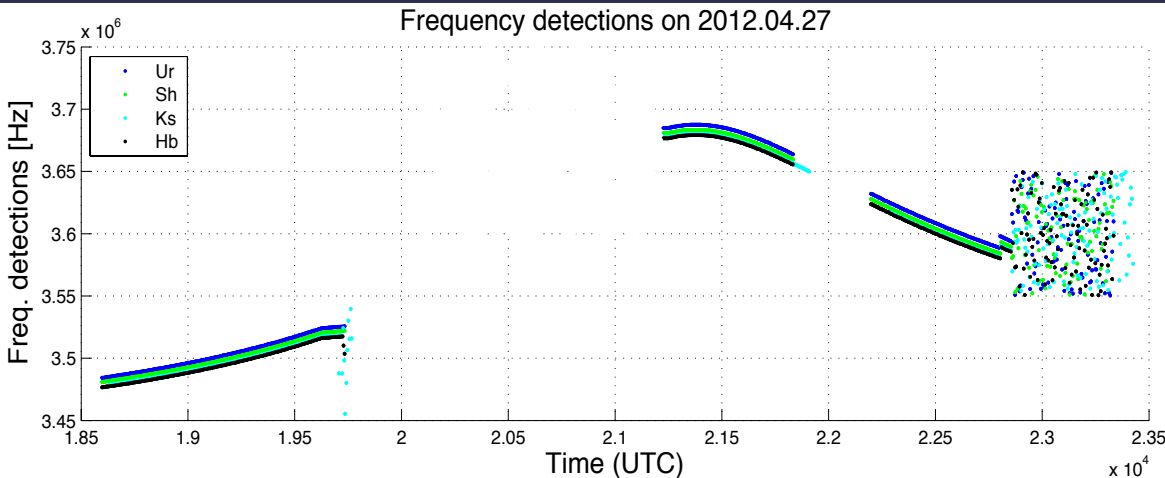
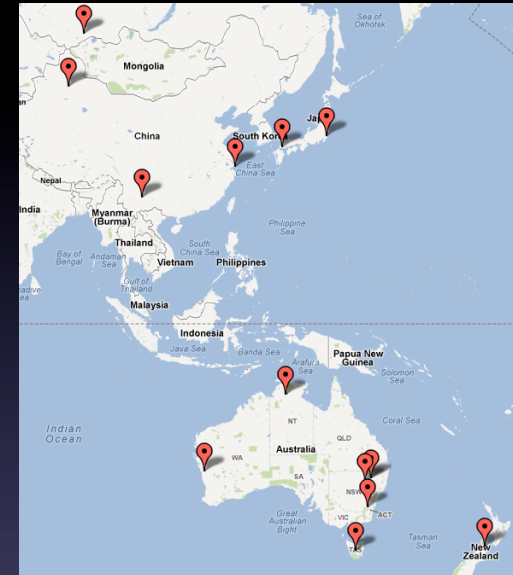
The effect of the gravity of Phobos is noticed in the propagation of the spacecraft signal in a jump on the signal phase.



(Molera et al. 2010 at the EPSC)

Other RS experiments

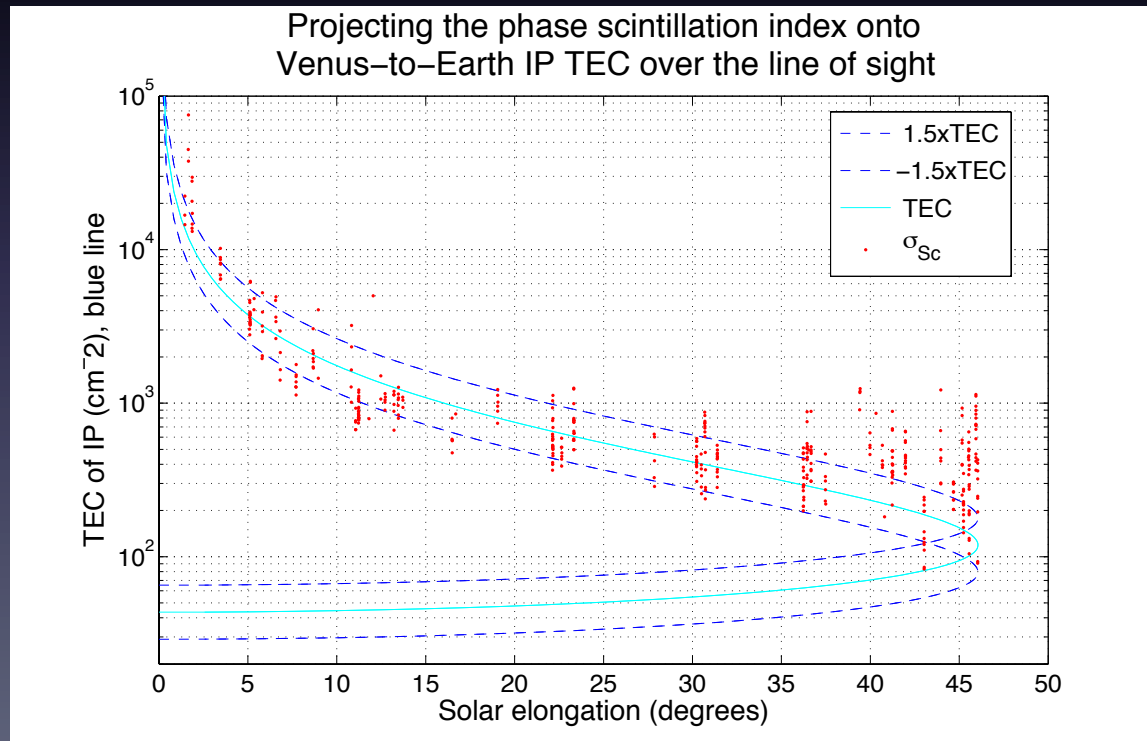
- **Venus Express Drag campaign**
- The orbit of the spacecraft is modified to pass near the periapsis.
- The campaign was carried out between 25 of April and 6 of May 2012:
In total, we observed 12 days of observations with an average of 3 telescopes per day.
- 12 (non-EVN) radio telescopes were arranged to conduct the observations.



Interplanetary scintillations

Phase scintillations on the spacecraft signal are caused by the propagation within the **solar wind**.

The VEX campaign has extended for more than 2 years and we used more than 15 antennas.



- ✓ Total electron content model of the interplanetary plasma at any distance and solar elongation.
- ✓ Determination of the optimal nodding cycle for phase-referencing.
- ✓ Determination of the best time for critical spacecraft operations (orbit insertion, descending, landing).

Conclusions

- High-precision tracking and orbit determination of (planetary) spacecraft is achievable with VLBI radio telescopes.
- PRIDE: Planetary Radio Interferometry and Doppler Experiment is a 'free' contributions to space mission.
- Future space missions include this initiative in their scientific package (BepiColombo, Marco-Polo, ExoMars, Gaia, JUICE,...).
- Better integration with next-generation of VLBI software correlators is in-process.
- Observations of Venus and Mars Express will continue in order to improve the processing pipeline for future planetary missions.